ARL-TR-95-21 Copy No. _______

Nonlinear Acoustics: Production of an Isolated Negative Pulse in Water, Self-Refraction in the Field of a Paraboloidal Reflector, and Preliminary Study of the Acoustitron

Sixth Annual Summary Report under Grant N00014-89-J-1109

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8 August 1995

Annual Report

Period
1 October 1993 - 30 September 1994

Approved for public release:
Distribution unlimited

Prepared for:
Office of Naval Research
ONR 331
800 North Quincy Street
Arlington, VA 22217-5660

UNCLASSIFIED

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	08 Aug 95	Annual Summary, 01 Oct 93 - 30 Sep 94

4. TITLE AND SUBTITLE
Nonlinear Acoustics: Production of an Isolated Negative Pulse in Water; Self-Refraction in the Field of a Paraboloidal Reflector, and Preliminary Study of the Acoustitron (Sixth Annual Summary Report under Grant N00014-89-J-1109)

5. FUNDING NUMBERS
PE 61153 N
G N00014-89-J-1109
TA 3126317

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Applied Research Laboratories
The University of Texas at Austin
P.O. Box 8029
Austin, Texas 78713-8029

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-95-21

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
ONR 331
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release:
Distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Research on nonlinear acoustics has been performed during the 12-month period ending 30 September 1994. Progress is reported on the following projects:

1. Production of an isolated negative pulse in water (experimental).
2. Self-refraction in the field of a paraboloidal reflector (experimental).
3. Preliminary study of the acoustitron (theoretical).

Public communication of the research includes one thesis, two oral papers, two journal articles published, three journal articles submitted, and one book chapter submitted.

14. SUBJECT TERMS

nonlinear acoustics	N waves	acoustitron
unipolar negative pulse	diffraction	toroidal waveguide
paraboloidal reflector	self-refraction	

15. NUMBER OF PAGES 29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

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1. INTRODUCTION

This is the sixth annual report under Grant N00014-89-J-1109, which began 1 October 1988. The research carried out under this grant is primarily in nonlinear acoustics. The broad purpose of the research is to determine the laws of behavior of finite-amplitude sound waves, especially to find generalizations of the known laws of linear acoustics. This report is for the period 1 October 1993 — 30 September 1994. See the fifth annual report (93-5)* for status of the research at the beginning of the current report period.

The following persons participated in the research during the report period:

Graduate students

- Michael R. Bailey, M.S. student in Mechanical Engineering; awarded M.S. degree May 1994. Ph.D. student beginning May 1994.
- Samuel C. Clark, M.S. student in Mechanical Engineering
- Lawrence J. Gelin, M.S. student in Mechanical Engineering

Undergraduate student

- Jamie M. Shorey, high school graduate

Although Bailey was supported by the IR&D Program of ARL:UT during most of the report period, his M.S. project had been supported during the previous two years by the ONR Grant, and his doctoral work, begun near the end of the report period, was supported by the Grant. Because of grade difficulties, Clark was not supported after the 1993 Fall Semester. Shorey, a 1994 summer student between high school graduation and enrollment as a freshman at Rice University, assisted Gelin on the paraboloidal reflector project. Her support, however, came from the Science and Engineering Apprenticeship Program of ARL:UT.

*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 93-5 means the fifth entry in the list for 1993.

Senior personnel

- W. M. Wright, Consultant, Physics Department, Kalamazoo College, Michigan
- D. T. Blackstock, principal investigator

Wright's effort was primarily to assist and advise Gelin on the paraboloidal reflector project.

2. PROJECTS

The following projects were active during the report period:

2.1 Production of an Isolated Negative Pulse in Water. This was an experimental project. An underwater spark produced a positive pressure pulse. Reflection and diffraction (from both smooth and ragged edges of plane barriers, apertures, and disks) were used to turn the positive pulse into a negative pulse and to block out the direct-path positive pulse.

2.2 Self-Refraction in the Field of a Paraboloidal Reflector. This was also an experimental project. The variation in particle velocity along the wavefront of an inhomogeneous plane wave causes the wavefront to bend. A paraboloidal reflector having a spark source at its focus was used to demonstrate the effect.

2.3 Preliminary Study of the Acoustitron. The acoustitron is a toroidal waveguide containing a progressive wave that is periodically boosted by appropriately phased sources. The occurrence of resonance at certain frequencies makes gain possible. The work was theoretical.

2.4 Other Projects

2.4.1 Nonlinear Effects in Propagation of Aircraft Noise

2.4.2 Miscellaneous

2.1 Production of an Isolated Negative Pulse in Water

This project was Bailey's M.S. topic. Although the actual research was completed during the previous report period (93-5), the part of the work done while Bailey was at the University of Rochester during the summer of 1993 led to the draft of a journal article (94-1) and an oral presentation (94-11). It also led Bailey to reorient his master's thesis, which was submitted for graduation in May 1994.

Described in Bailey's thesis are three methods for producing an isolated negative pressure pulse in water. Each starts with an underwater spark, which produces a nearly unipolar positive pulse. Two of the three methods rely on reflection from the air-water surface to produce the desired negative pulse. However, reflection by itself is

not satisfactory because the target (biological tissue in Bailey's case) is then exposed to two pulses: the positive direct pulse as well as the negative reflected pulse. In method (1) the positive pulse is blocked by placing an irregular-edge disk between the spark and the target. The purpose of the irregular edge is to prevent the formation of a coherent edge wave (if the disk were simply circular, the edge wave would be a delayed replica of the direct, positive pulse). In method (2), a plane barrier is used instead of the disk. However, the barrier must have an irregular edge, again to destroy the coherence of the edge wave. Method (3) does not make use of reflection from the air-water surface. Instead the negative pulse is generated as the edge wave from a circular aperture (94-8). When the aperture is aligned between the source and target, the edge wave at the target is a delayed but inverted replica of the incident wave. Again, however, the direct, positive wave must be removed. It is blocked by locating an irregular-edge disk in the aperture. All three methods were tried and produced the desired isolated negative pulse. Method (2), however, proved most practical and convenient for the tissue exposure experiments. The experiments showed that isolated positive pulses are at least as damaging as negative pulses to mouse lungs and to fruitfly larvae (94-1, 94-11). This is an important finding. Heretofore investigators have assumed that tissue damage is due primarily to negative pressure.

2.2 Self-Refraction in the Field of a Paraboloidal Reflector

This is the M.S. project of Gelin, who was assisted during the summer of 1994 by Shorey. Self-refraction is bending of rays due solely to finite-amplitude effects, as opposed to ordinary refraction, which is caused by sound speed variation in an inhomogeneous fluid. The propagation speed of a finite-amplitude wave is

$$\frac{dx}{dt} = c_0 + \beta u \quad , \tag{2.1}$$

where c_0 is the small-signal sound speed, β is the coefficient of nonlinearity, and u is the particle velocity. Because of the dependence of dx/dt on u, any variation of the particle velocity along a wavefront causes a change in direction of the wavefront, i.e., refraction. Self-refraction was first proposed by Whitham for shock waves.[1,2]

Self-refraction is not very well known in nonlinear acoustics and not often mentioned in the literature. One of the reasons is that it is difficult to find a simple experiment with which to verify the effect. Self-refraction has been demonstrated for medium-strength shock waves in a shock tube.[3] To the writer's best knowledge, however, the phenomenon has not been observed in the realm of nonlinear acoustics. Barger and coworkers[4] attempted to show that self-refraction could prevent focusing of an N wave by a spherical mirror. Focusing is a strong effect, however, and their N waves were too weak to overcome it. Although self-refraction undoubtedly occurs in

intense beams of periodic sound, its effect is probably masked by diffraction, which is usually a more powerful phenomenon.

We inadvertently encountered evidence of self-refraction in an experiment done by Hester for a master's report in 1992.[5] Hester used a spark source at the focus of a paraboloidal reflector to produce what was expected to be a plane N wave field. The plane waves produced in this way are, however, inhomogeneous. That is, although the rays reflected from the paraboloid are all parallel to the axis, the amplitude is not the same for each ray. The amplitude is determined by the spherical spreading that occurred while the wave traveled from the spark source to the surface of the reflector. Since the spreading is least for the axial ray and greatest for the rays reflected at the edge of the paraboloid, the reflected field is strongest on the axis and weakest at the edge of the beam. In particular, a ray theory calculation shows that the variation of the pressure $p(R)$ across the beam, where R is distance perpendicular to the axis, is given by

$$\frac{p(R)}{p(0)} = \frac{1}{1+(R/2z_F)^2} \quad . \tag{2.2}$$

Here $p(0)$ is the axial pressure and z_F is the focal length. Hester confirmed Eq. (2.2) by a measurement made 10 cm in front of the aperture. See Fig. 2.1. The machined aluminum paraboloid he used has focal length $z_F = 5.08$ cm, depth $d = 4.88$ cm,

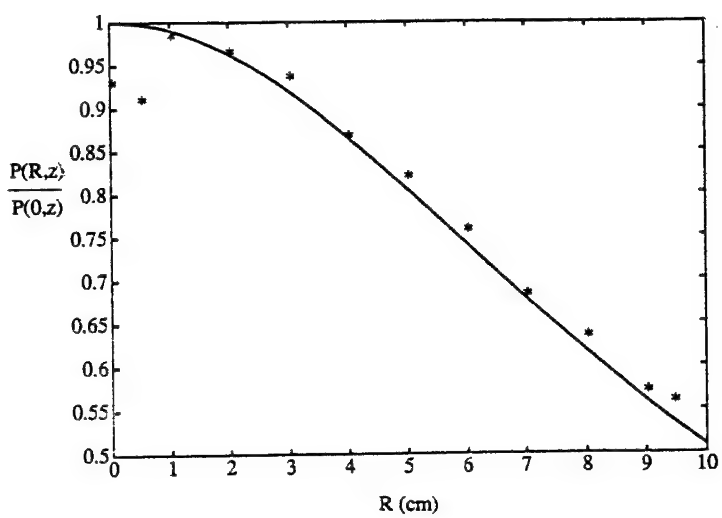

Figure 2.1
Pressure across the beam 10 cm in front of a paraboloidal reflector. Solid curve represents Eq. (2.2), asterisks the measurements. From Ref. 5
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and aperture radius $a = 10.80$ cm. As the figure shows, for the conditions of the

experiment the pressure at the edge of the beam is about half that on the axis.*

Despite the success with Eq. (2.2), however, certain plane wave formulas that were to be used for Hester's intended application did not work. The apparent reason is that the field began to become nonplanar and spread much earlier than had been expected. Self-refraction is a logical explanation for the spreading. To test this hypothesis, Gelin was given the task of making much more detailed measurements of the field of a paraboloidal reflector and comparing them with what could be expected. After Hester's brief study, we realized that the paraboloidal reflector is ideal for studying self-refraction. No competition from focusing exists and, because of the weakness of the edge wave,[6] the effect of diffraction is muted.

Gelin started by making some initial calculations to determine the magnitude of the self-refraction effect for his experiment, which was to be done with the same machined aluminum reflector used by Hester. He found expected differences (across the beam) in the delay of the peak, zero crossing, and trough of the N wave to be of the order of μs. This meant that the positioning system that holds the reflector, spark source, and microphone had to be very carefully aligned. Very weak sparks, which produce N waves weak enough not to self-refract, were used to test the alignment. With very careful work, he was able to traverse the beam 15 cm from the aperture and observe a maximum difference in arrival time of only 0.5 μs. Considerable attention also had to be paid to the triggering of the spark.

When he repeated Hester's measurements, with much the same apparatus, Gelin confirmed the unexplained dip in the N wave signal near the axis. Four possible causes were initially considered.

(1) Diffraction from a small hole drilled in the center of the reflector (used to pass a laser beam for optical alignment).

(2) Diffraction from the spark electrode tips.

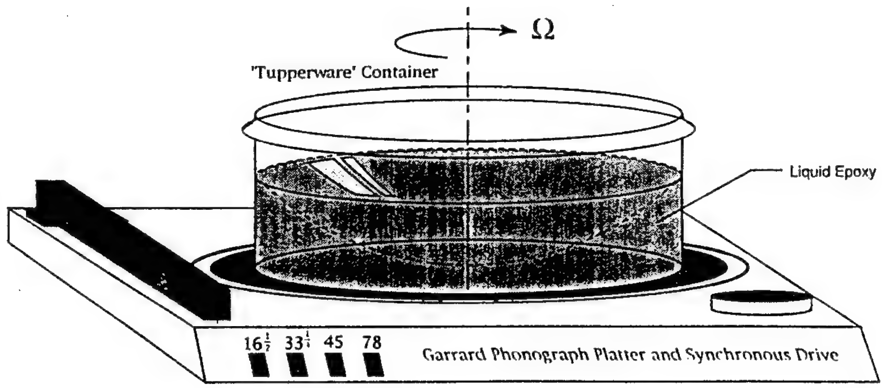
(3) Imperfections in the machined surface of the aluminum reflector.

(4) Refraction of the axial rays by the small volume of hot gas created by the spark. This was Hester's explanation.[5]

The first two possibilities were quickly disposed of. The third was checked by making a new reflector by a different method (described below). The fourth became the subject of a theoretical investigation that had not been completed by the end of the report period.

*The local drop in peak pressure on and near the axis is believed not to be due to self-refraction. The drop is discussed in more detail later in this section.

Shorey, Gelin's assistant for the summer, constructed a second paraboloid by a novel method: spinning a container of epoxy. Since the surface of a rotating liquid is a paraboloid, when the epoxy hardens, a perfect paraboloidal reflector is obtained. An old record player (see Fig. 2.2) was used to spin the liquid, and the epoxy was spun and



$$F = \frac{g}{2\Omega^2}$$

F = focal length
Ω = rotational speed, rad/s
$g = 9.81\ \mathrm{m/s^2}$

Figure 2.2
Making a paraboloidal reflector by spinning a liquid AS-95-992

hardened in layers. The final surface was exceedingly smooth and free of bumps. The dimensions are as follows: $z_F = 5.17$ cm, $a = 10.05$ cm, and $d = 4.88$ cm. These were intentionally make similar to those of the machined aluminum reflector so that the third possibility for the cause of the axial dip could be checked. Although the epoxy reflector had a much smoother surface than the aluminum reflector, measurements of its reflected field also showed the same axial dip in the N wave signal. This test helped convince us that the fourth possibility, a small pocket of hot gas caused by the spark, is the most likely cause of the dip.

Oral reports on the project were given shortly after the end of the report period (94-9, 94-10). A good summary of the project, at approximately the end of the report period, is given by the following (slightly edited) excerpt from the abstract for 94-10: "An experimental investigation of the transient response of a paraboloidal reflector is reported. An inhomogeneous plane N wave was produced by locating an electrical spark at the focus of a machined aluminum paraboloidal reflector (focal length $z_F = 5.08$ cm, radius $a = 10.80$ cm). A second reflector ($z_F = 5.17$ cm, $a = 10.05$ cm) was constructed by spinning a container of epoxy at constant speed and allowing it to cure. Peak pressure P and arrival time were measured across the beam (fixed axial distance z measured from the reflector surface, variable radial distance R) and along the axis. The range of the measurements was $R \leq 80$ mm

and 20.74 mm $\leq z \leq$ 95.74 mm. Small-signal N waves (P = 400 Pa, duration T = 9 μs) were measured as well as stronger ones (P = 1000 Pa, T = 12 μs). For small-signal N waves the axial measurements generally confirm Hamilton's theoretical prediction (previous paper, 1pPA4) although the edge waves are weaker than forecast. Transverse measurements agree with ray-theory predictions off axis but are up to 10% low in the axial region. For stronger N waves, transverse measurements of arrival time and peak pressure show evidence of self-refraction (ray bending due solely to finite-amplitude effects)."

2.3 Preliminary Study of the Acoustitron

Bailey investigated two different problems as possible doctoral dissertation projects. First was the acoustitron, which is described briefly here. Second was a two-ellipsoid lithotripsy device, but because it was not considered until after the report period ended, it will be taken up in the report for 1994-95. Although the eventual decision was that the two-ellipsoid project should be Bailey's doctoral research topic, enough work was done on the acoustitron to describe the initial results here.

The acoustitron is a waveguide in the form of a loop that closes on itself, that is, it has a toroidal shape like a tire inner tube. Appropriately phased sources establish a progressive wave field inside the toroid. If the source frequency is chosen so that the circumference C of the toroid is an integral number of wavelengths λ, then as the wave completes a lap, it and the sound supplied by the sources add constructively. A resonance is thus established, yet the sound field is still progressive. The benefits of resonance suggest that it may be possible to generate a very intense progressive sound field in the toroid.

We considered two methods of driving the acoustitron. In the first method two or more conventional sources, such as horn drivers or piezoelectric elements, are spaced at intervals around the loop and are phased so that their emissions add constructively in one direction. At least two sources are required; a single source would set up a standing wave, since it could not by itself provide any directional bias. The second method makes use of an acoustical analog of the microwave directional coupler. See Fig. 2.3. A progressive wave is set up in a conventional straight, anechoically terminated plane wave tube. The side wall of the straight tube and the toroid share two or more slits. Sound escaping into the toroid through the slits is perfectly phased to generate a progressive wave in the toroid. This method was suggested to us by R. M. White.[7]

Although quite novel, the acoustitron is not new. To the best of our knowledge, the initial idea came from H. E. von Gierke, who gave the device its name

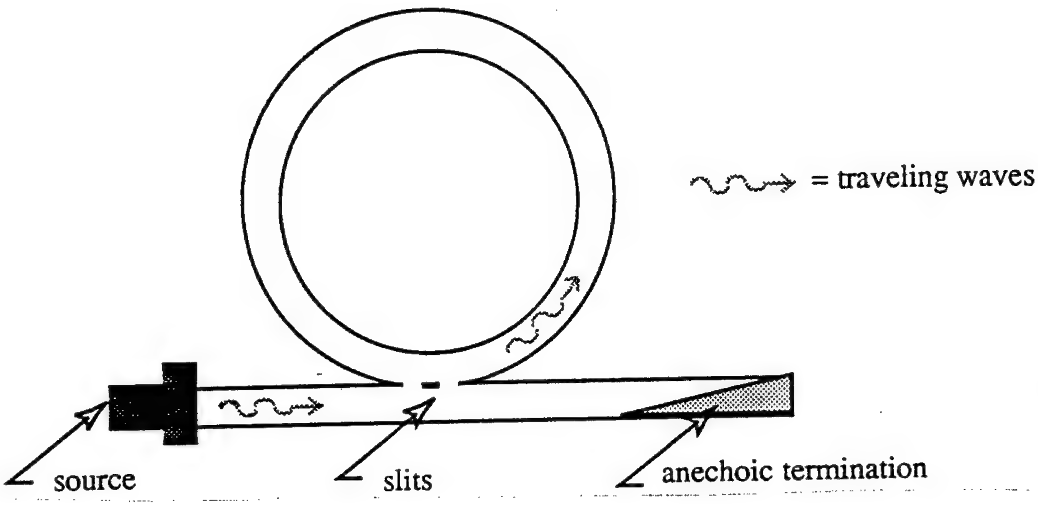


Figure 2.3
Acoustitron driven by a "directional coupler"

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(an "acoustical cyclotron"). He was interested in producing a very intense progressive wave sound field in which to test electronic and mechanical components for the aerospace industry. The conventional acoustical test chamber makes use of standing waves to achieve a very intense reverberant field. The acoustitron would offer a more realistic test environment, that is, one closer to the sound fields produced in the open by aircraft and rockets. At Wright-Patterson AFB about 1960, von Gierke showed Blackstock a model acoustitron made out of a copper tube.[8] His device resembled the one shown in Fig. 2.3, but without the second half of the straight tube. He reported sound pressure levels up to 160 dB at resonance. Blackstock tried to replicate von Gierke's results but without success, for reasons that are now clear: the drive used did not bias against standing waves in the toroid.[8] Independently, the acoustitron idea resurfaced 30 years later at NCPA. Lawrenson and Shields demonstrated the feasibility of the acoustitron by using a sequence of piezoelectric rings to squeeze the wall of a small toroidal waveguide.[9] They achieved a sound pressure level of about 110 dB for resonance frequencies in the range 250 Hz to 2.8 kHz.

Some preliminary theoretical results were obtained during the report period. First is a linear theory calculation of the steady state amplitude achieved by an acoustitron when small-signal attenuation (tube wall absorption, for example) is present. Recall that C is the circumference of the acoustitron. For purposes of calculation let the field be modeled as a progressive wave in a semi-infinite straight tube having sources spaced periodically at intervals of C along the length of the tube. If A is the amplitude produced by a source, then $Ae^{-\alpha x}$ is the amplitude a distance x away from that source, where α is the attenuation coefficient. At resonance ($C = m\lambda$, where m is an integer)

all the waves produced by the sources are in phase. At the nth source the pressure due to that source and the $n-1$ preceding sources is

$$p = A + Ae^{-\alpha C} + Ae^{-\alpha 2C} + Ae^{-\alpha 3C} + \cdots Ae^{-\alpha nC} \quad , \tag{2.3}$$

which sums to

$$p = A\frac{1 - e^{-(n+1)\alpha C}}{1 - e^{-\alpha C}} \quad . \tag{2.4}$$

This represents the amplitude after the wave has made n laps around the toroid. The steady state amplitude is found by taking the limit as n becomes very large: $p = A/(1 - e^{-\alpha C})$. The gain G due to resonance is thus

$$G = \frac{1}{1 - e^{-\alpha C}} \quad . \tag{2.5}$$

To achieve a high steady state level, therefore, the loss in one lap around the toroid must be small. Figure 2.4 shows the growth of the amplitude for various values of αC as a function of the number of laps around the toroid.

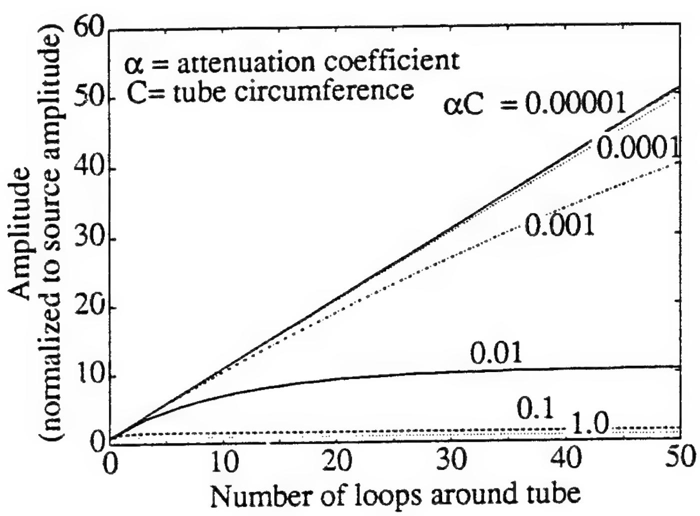

Figure 2.4
Linear theory: growth of amplitude in the acoustitron limited by small-signal attenuation

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The second theoretical result is for finite-amplitude waves in an acoustitron. The waveform of an ordinary plane progressive wave of finite amplitude is well known. When the wave is strong, the fundamental is continually depleted by transfer of energy to the harmonics, and distortion ultimately produces a sawtooth waveform.

In the case of the acoustitron, however, the fundamental is periodically increased. Our preliminary calculations, done with a frequency-domain numerical code,[10] show that the steady state waveform is not a sawtooth. See Fig. 2.5. The acoustitron waveform more closely resembles that of an ordinary wave a little past the shock formation stage. Moreover, the steady state waveform is indeed steady state. In the case of the ordinary finite-amplitude wave, no true steady state waveform exists. The sawtooth slowly decays and eventually reverts to sinusoidal shape in old age.

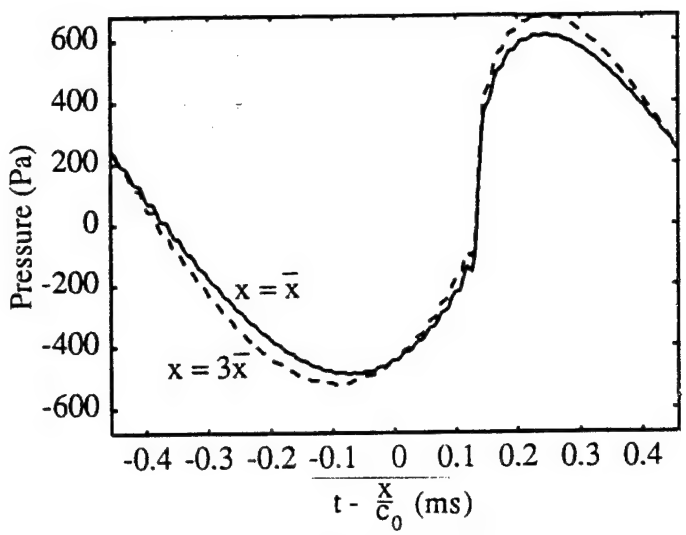

Figure 2.5
Waveforms of the steady state wave in an acoustitron. $P_0 = 100$ Pa, $f_0 = 1092$ Hz, $C = 1.571$ m, and tube radius $a = 0.5$ in. (0.0127 m). The quantity $\overline{x}$ is the shock formation distance for an ordinary plane wave from a source at $x = 0$, amplitude P_0. (For case shown $\overline{x} = 59.3$ m.)

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2.4 Other Projects

2.4.1 Nonlinear effects in propagation of aircraft noise

A major task in aircraft noise is prediction of the noise level in a community at some distance from an aircraft, given the known spectrum near the aircraft. All the prediction algorithms currently in use are based on linear theory. They include spherical spreading, atmospheric absorption, and even refraction effects. The predictions are generally good, but they often underpredict the 1/3 octave band levels at high frequencies, sometimes by very substantial amounts. Moreover, the error increases

with frequency and with distance from the aircraft. For F4C noise, for example, W. R. Lundberg[11] found measured propagation curves for 1/3 octave bands centered at 5, 6.3, 8, and 10 kHz to lie substantially above predicted curves based on a linear theory algorithm. At a distance of 1539 ft the prediction curves are too low by 7 dB for the 5 kHz band, 15 dB for the 6.3 kHz band, 27 dB for the 8 kHz band, and 45 dB for the 10 kHz band.

Does finite-amplitude distortion provide a quantitative explanation for the propagation curves of the high frequency bands? Clark's project was to have provided an answer to this question. Unfortunately, however, although Clark became oriented on the problem during the 1993 fall semester, his grades were not good enough for him to continue. The project therefore ceased being one supported by the Grant. Later (in 1994) NASA sponsorship was obtained to continue the project, and two students began work on it.

2.4.2 Miscellaneous

Although C. E. Bradley's project on waves in a periodic waveguide (see 93-5, Sec. 2.1) ended during the previous report period, during the current period his dissertation was issued as a technical report (93-1), two journal articles were published (94-5, 94-6), a third was submitted (94-4), and a paper was presented at an Acoustical Society Meeting (93-8).

Another project completed during the previous report period was P. Li's theoretical analysis of finite-amplitude waves in a medium having a distribution of relaxation processes (see 93-5, Sec. 2.2). During the current period a paper was presented at an Acoustical Society Meeting (93-9) and a journal article was submitted (94-2).

Finally, Blackstock submitted a review chapter on nonlinear acoustics for publication in a handbook (94-7).

3. SUMMARY

During the current report period, 1 October 1993 – 30 September 1994, research was done on the following principal projects (student's names shown in parenthesis):

1. Production of an isolated negative pulse in water (Bailey)
2. Self-refraction in the field of a paraboloidal reflector (Gelin, Shorey)
3. Preliminary study of the acoustitron (Bailey)

Project 1, begun in 1991, was brought to a conclusion. Bailey's M.S. thesis (94-3) describes three ways of producing an isolated negative pulse when the source is an underwater spark. The project also produced four oral papers (92-3, 93-3, 94-8, 94-11), a conference proceedings paper (93-3), and a journal article submitted for publication (94-1). Project 2 began this year. The experiment was set up, preliminary measurements were made, and excellent alignment of the spark, reflector, and microphone was achieved. A new paraboloidal reflector was made by spinning a container of epoxy. Two oral papers were given shortly after the end of the report period (94-9, 94-10). Project 3 was a preliminary investigation, entirely theoretical during the report period, of a toroidal waveguide having sources phased to produce resonance in a progressive wave.

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1988–1994
Grant N00014-89-J-1109
and
Predecessor Contract N00014-84-K-0574 (ended 9-30-88)

		Code			ONR Grant/Contract
B	=	chapter in a book	1109	=	N00014-89-J-1109, began 10-1-88
J	=	journal publication			
Js	=	submitted for journal publication	0574	=	N00014-84-K-0574, ended 12-31-88
O	=	oral presentation			
P	=	paper in a proceedings			
T	=	thesis or dissertation	0867	=	N00014-75-C-0867 ended 8-31-84
TR	=	technical report			

1988

ONR Contract	Code		
0574	J	[a]1.	M. F. Hamilton and D. T. Blackstock, "On the coefficient of nonlinearity β in nonlinear acoustics," *J. Acoust. Soc. Am.* **83**, 74–77 (1988).
0574	O	[b,c]2.	D. T. Blackstock, "Shock wave propagation and shape of the waveform," Conference on Lithotripsy (Extra-Corporeal Shock Wave Applications - Technical and Clinical Problems), University of Florida, Gainesville, Florida, 12–13 March 1988.
0574	O	[b]3.	D. T. Blackstock, "Calculation of the intensity and absorption of a finite-amplitude sound wave," Paper B8, 115th Meeting, Acoustical Society of America, Seattle, 16-20 May 1988. ABSTRACT: *J. Acoust. Soc. Am.* **83**, S5 (1988).
0574	O	[b]4.	D. T. Blackstock, "Physical aspects of lithotripsy," Paper GG1, 115th Meeting, Acoustical Society of America, Seattle, 16-20 May 1988. ABSTRACT: *J. Acoust. Soc. Am.* **83**, S71 (1988).

[a]Hamilton's support for this work came from Contract N00014-85-K-0708.
[b]Primary support for this work came from University of Rochester, NIH Grant CA 39241.
[c]Supported in part by a grant from Bureau of Engineering Research, College of Engineering, The University of Texas at Austin.

ONR Contract	Code		
0574	TR	5.	D. T. Blackstock, "Nonlinear Acoustics: Reflection and Refraction, Scattering of Sound by Sound, and Periodic Media," Fourth Annual Summary Report under Contract N00014–84–K–0574, Technical Report ARL–TR–88–30, Applied Research Laboratories, The University of Texas at Austin, 30 June 1988 (AD A197614).
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Gen§	O	7.	D. T. Blackstock, I. J. Busch-Vishniac, M. F. Hamilton, and E. L. Hixson, "Graduate acoustics at The University of Texas at Austin," Paper ZZ9, 116th Meeting, Acoustical Society of America, Honolulu, 14-18 November 1988. ABSTRACT: *J. Acoust. Am.* 84, S167 (1988).

§Supported in part by ONR, under several different grants and contracts, and by several other sponsors.

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1109 0574	T,TR	1.	F. D. Cotaras, "Reflection and Refraction of Finite Amplitude Acoustic Waves at a Fluid-Fluid Interface," Ph.D. dissertation, Electrical and Computer Engineering Department, The University of Texas at Austin, May 1989. Also issued as Technical Report ARL-TR-89-1, Applied Research Laboratories, The University of Texas at Austin (3 January 1989). (AD A209800) ABSTRACT: *J. Acoust. Soc. Am.* **92**, S201 (1991).
1109	O	[d]2.	D. T. Blackstock, S. Cheng, M. R. Jones, and W. M. Wright, "Focusing of intense sound pulses by an ellipsoidal reflector," Paper BE12, Joint Spring Meeting, Texas Sections of American Association of Physics Teachers and American Physical Society, University of Houston, Houston, 3–4 March 1989.
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[d]Primary support for this work came from Applied Research Laboratories IR&D Program and Texas Advanced Research Program.

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[e]Supported in part by Applied Research Laboratories IR&D Program.

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[f]Maynard's support for this work came from an ONR contract at Pennsylvania State University.
[g]Supported in part by NIH Grant CA 49172 and by University of Rochester NIH Grant CA 39241.

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[h]Primary support for this work came from NASA Grant NSG 3198.
[i]Hamilton's support for this work came from Grant N00014-89-J-1003.
[j]Supported in part by Grant N00014-J-90-1373.

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1109	TR	5.	D. T. Blackstock, "Nonlinear Acoustics: Propagation in a Periodic Waveguide, Scattering of Sound by Sound, Propagation Through a Three-Layer Fluid, and Nonlinearity Parameters of Sea Water," Third Annual Summary Report under Grant N00014-89-J-1109, Technical Report ARL-TR-91-21, Applied Research Laboratories, The University of Texas at Austin, 19 August 1991. (AD A241294)
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[k]Supported in part by Grant NAG-1-1204 and University of Southampton, England.

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[l]Supported in part by ONR Grant N00014-89-J-1103, Applied Research Laboratories IR&D Program, and David and Lucille Packard Foundation.
[m]Supported in part by NIH grant at University of Rochester.
[n]Supported in part by NIH Grant CA 41972.

1993

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1109	O	10.	L. J. Gelin, J. M. Shorey, D. M. Hester, and D. T. Blackstock, "Experimental study of the reflection of airborne, spark-produced N waves by a parabolic dish," Paper 1pPA5, 128th Meeting, Acoustical Society of America, Austin, 28 November–2 December 1994. ABSTRACT: *J. Acoust. Soc. Am.* **96**, 3226(A) (1994).
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